

AD/A-006 519

UTILIZATION OF SYNTHETIC SOILS IN  
ENGINEERING RESEARCH

Andrew J. Green

Army Engineer Waterways Experiment  
Station  
Vicksburg, Mississippi

June 1971

DISTRIBUTED BY:

**NTIS**

National Technical Information Service  
U. S. DEPARTMENT OF COMMERCE



MISCELLANEOUS PAPER M-71-5

# UTILIZATION OF SYNTHETIC SOILS IN ENGINEERING RESEARCH

by

A. J. Green



June 1971

Sponsored by Assistant Secretary of the Army (R&D), Department of the Army  
Project 4A061101A91D

Conducted by U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

ARMY-MRC VICKSBURG, MISS.

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

*ii*

Unclassified  
Security Classification

AD/A-006519

DOCUMENT CONTROL DATA - R & D		
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)		
1. ORIGINATING ACTIVITY (Corporate author)		2A. REPORT SECURITY CLASSIFICATION
U. S. Army Engineer Waterways Experiment Station Vicksburg, Mississippi		Unclassified
		2B. GROUP
3. REPORT TITLE		
UTILIZATION OF SYNTHETIC SOILS IN ENGINEERING RESEARCH		
4. DESCRIPTIVE NOTES (Type of report and inclusive dates)		
Final report		
5. AUTHOR(S) (First name, middle initial, last name)		
Andrew J. Green		
6. REPORT DATE	7A. TOTAL NO. OF PAGES	7B. NO. OF REFS
June 1971	20	6
8A. CONTRACT OR GRANT NO.	8B. ORIGINATOR'S REPORT NUMBER(S)	
8. PROJECT NO. 4A061101A91D	Miscellaneous Paper M-71-5	
9.	9B. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
4.		
10. DISTRIBUTION STATEMENT		
Approved for public release; distribution unlimited		
11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY
		Assistant Secretary of the Army (R&D), Department of the Army, Washington, D. C.
13. ABSTRACT		
<p>This report summarizes published results and personal comments of a number of re-researchers who have used synthetic soil mixtures. It also contains a small amount of data collected at the Waterways Experiment Station. In general, it can be said that whereas synthetic soils may be useful in some limited sense, they do not offer the panacea that earlier researchers claimed or hoped for. The engineering properties of many synthetic mixes may be more dependent on temperature and rate of loading than those of soil-water mixes. It is concluded that the usefulness of synthetic soils in engineering research is rather limited, and it is recommended that any researcher thoroughly study the behavioral patterns peculiar to a particular synthetic mix he may plan to use lest the utility of the information produced be restricted by them.</p>		

Reproduced by  
NATIONAL TECHNICAL  
INFORMATION SERVICE  
US Department of Commerce  
Springfield, VA. 22151

DD FORM 173 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS  
NOV 60 1-973 OBSOLETE FOR ARMY USE.

Unclassified  
Security Classification

Unclassified  
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Synthetic soils						

Unclassified  
Security Classification

ia

### Foreword

The study reported herein was conducted during the period 1969-1970 and was funded by Project 4A061101A91D, "In-House Laboratory Independent Research, Use of Synthetic Soils in Engineering Research - A Feasibility Study," sponsored by the Assistant Secretary of the Army (R&D).

The project was directed by Mr. A. J. Green, Research Projects Group, Mobility Research Branch (MRB), Mobility and Environmental (M&E) Division, at the U. S. Army Engineer Waterways Experiment Station (WES). The test program was carried out by personnel of the MRB under the general supervision of Mr. W. G. Shockley, Chief, M&E Division, and Mr. S. J. Knight, Assistant Chief, M&E Division, and Chief, MRB. The report was prepared by Mr. Green.

COL Levi A. Brown, CE, and COL Ernest D. Peixotto, CE, were Directors of WES during this study. Mr. F. R. Brown was Technical Director.

## Contents

	<u>Page</u>
Foreword. . . . .	iii
Conversion Factors, British to Metric Units of Measurement. . . . .	vii
Summary . . . . .	ix
Introduction. . . . .	1
Background. . . . .	1
Purpose and scope . . . . .	2
Synthetic Soils . . . . .	2
Users . . . . .	2
Categories. . . . .	3
Several synthetic soils and their uses. . . . .	3
Advantages sought . . . . .	4
Preparation and Maintenance of Test Soils . . . . .	4
Natural soils . . . . .	4
Synthetic soils . . . . .	5
Comparative Tests of Natural and Synthetic Soils. . . . .	6
Tests by Selig and Rowe . . . . .	6
Tests at WES. . . . .	6
Disadvantages of Synthetic Soils. . . . .	8
Ongoing Research. . . . .	9
Conclusions and Recommendations . . . . .	10
Conclusions . . . . .	10
Recommendations . . . . .	10
Selected Bibliography . . . . .	11
Personal Correspondence . . . . .	11
Figures 1-4	

### Conversion Factors, British to Metric Units of Measurement

British units of measurement used in this report can be converted to metric units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
inches	2.54	centimeters
inches per minute	2.54	centimeters per minute
pounds per square inch	6.8948	kilonewtons per square meter
Fahrenheit degrees	5/9	Celsius or Kelvin degrees*

---

\* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula:  $C = (5/9)(F - 32)$ . To obtain Kelvin (K) readings, use:  $K = (5/9)(F - 32) + 273.15$ .

### Summary

This report summarizes published results and personal comments of a number of researchers who have used synthetic soil mixtures. It also contains a small amount of data collected at the Waterways Experiment Station. In general, it can be said that whereas synthetic soils may be useful in some limited sense, they do not offer the panacea that earlier researchers claimed or hoped for. The engineering properties of many synthetic mixes may be more dependent on temperature and rate of loading than those of soil-water mixes. It is concluded that the usefulness of synthetic soils in engineering research is rather limited, and it is recommended that any researcher thoroughly study the behavioral patterns peculiar to a particular synthetic mix he may plan to use lest the utility of the information produced be restricted by them.



# UTILIZATION OF SYNTHETIC SOILS IN ENGINEERING RESEARCH

## Introduction

### Background

1. Engineering research studies that involve the use of soil can be very costly, and a large portion of the cost is attributable to the soil preparation. Inability to maintain stable conditions during the testing cycle plagues research programs involving natural soils both in the laboratory and in the field. This instability may be caused by a variety of factors, including moisture evaporation and thixotropic changes.

2. In the past, several researchers have attempted to use "synthetic soils," particularly in model studies; and whereas some seem quite pleased with their results, as many others are thoroughly displeased. However, a comprehensive comparison has not been made of the properties of natural and synthetic soils sufficient in scope to permit a prospective researcher to truly and objectively judge the relative merit of using synthetic soils.

3. There appear to be a number of possible advantages in using such materials. One possibility is the establishment of a standard reference material for a broad group of research programs being conducted in laboratories throughout the country. Also, such materials may have long-term stability, reproducibility of test conditions may be enhanced, and economic advantages may result in some instances. These possibilities alone seem to justify a comprehensive study of the properties of synthetic materials, and a comparison of their properties with those of natural soils.

4. There are a number of direct potential uses for synthetic soils in the defense-related research programs being conducted at the U. S. Army Engineer Waterways Experiment Station (WES). Among these are:

- a. The development of design criteria and performance prediction methods for structures intended to provide protection against nuclear weapons.
- b. The development of methodology for predicting and evaluating the performance of off-road vehicles and of aircraft landing gear assemblies designed for operation on unsurfaced landing strips.

- c. The development of technology for designing and predicting the operational life of pavements (prefabricated, flexible, and rigid).
- d. The examination of the effects of explosive charges as a means of rapid earth excavation.

5. Unfortunately, sufficient funds for a comprehensive study are not available. Nevertheless, because WES personnel, in their association with engineers and scientists in many fields of research, have frequently been questioned regarding their opinion and/or that of the WES on the use of synthetic soils for various types of projects, this limited study was undertaken. This report contains the data available at the WES and comments of others currently active in the use of synthetic soils.

#### Purpose and scope

6. The purposes of this study were to:
- a. Review and record some of the uses of synthetic soils in the past decade.
  - b. Evaluate the advantages and disadvantages of using synthetic soils in lieu of soil-water mixtures.

These evaluations were based on considerations of preparation and maintenance, the relative magnitude of certain engineering properties, and long-term stabilities of the mixtures.

7. This program was limited to a literature review, communication with certain researchers experienced in the use of synthetic soils, and a limited amount of laboratory testing at the WES. The scope of this testing was limited to two clays mixed with several different pore fluids. The tests included evaluation of shear strength and of the effects of temperature and rate of penetration on penetration resistance.

### Synthetic Soils

#### Users

8. To list all of the governmental organizations, industries, and universities that have used, are using, or tentatively plan to use synthetic soils is impractical; and to solicit comments from more than a selected few of the many possible users is equally impractical. Over the past

few years, the following agencies have been contacted: U. S. Army Tank-Automotive Command, National Aeronautics and Space Administration, U. S. Department of Agriculture, U. S. Department of the Navy, Caterpillar Tractor Company, John Deere Company, Illinois Technology Research Institute, State University of New York, and Stevens Institute of Technology.

#### Categories

9. Synthetic soils fall into several different categories. These are:

- a. Entirely synthetic. For example, the use of gelatin to represent a cohesive material; glass beads or rods to simulate a purely frictional material; mixtures of beads and oil to simulate soil with both strength components, etc.
- b. Synthetic pore fluids and/or binders. The combining of a single type of soil with a synthetic pore fluid or combination of pore fluids or with synthetic binding material, e.g. clay and glycol, sand and oil, asphalt and sand, etc.
- c. Synthetic admixtures. Any mixture of two or more natural soils with artificial pore fluids, binders, or other non-soil substances.

#### Several synthetic soils and their uses

10. Gelatin has been used to study stress patterns created by loading cohesive materials with model structure foundations and wheels. Glass beads and smooth rods have been used to represent frictional materials for the study of displacements generated by surface loading and by running wheels.

11. Natural soils with synthetic pore fluids (binders), as well as synthetic admixtures, have been used in studies of earthmoving equipment (scale models), effects of explosive charges, transient loading, tillage tools, vehicle mobility, etc.

12. Two common synthetic admixtures are clay-sand-oil and clay-sand-ethylene glycol with various percentages of the three constituents. Glycerin has also been used as a pore fluid in such mixes. These admixtures have been used in a variety of applications covering generally the same areas as listed in paragraph 10 above.

13. One researcher reported that he had produced a satisfactory synthetic soil for his needs by mixing kaolinite with two liquids from the

family of plasticizers, dibutyl phthalate and dibutyl sebacate. The mixture of fluids was assigned the name Hydrate 121.

#### Advantages sought

14. The emphasis on the type of advantages sought may differ from one researcher to another, but there is a certain amount of commonality. A few of the advantages that have been mentioned are:

- a. Long-term stability of the mix.
  - (1) Low evaporation rate
  - (2) No serious thixotropic changes
  - (3) No aggregation or disaggregation with time
  - (4) Repeatability of conditions
- b. Establishment of standard (reference) materials for laboratories doing similar research throughout the country.
- c. Economic gains. Although the initial cost of many synthetic soils or soil simulants may be high, there is the potential savings resulting from the lack of a need to remix certain materials with their pore fluids after long storage periods.

#### Preparation and Maintenance of Test Soils

##### Natural soils

15. The WES has had considerable experience in preparing and maintaining large volumes (up to several hundred cubic yards in a single test specimen) of soil-water mixtures in its mobility research programs. Two fine-grained soils (a heavy clay and a lean clay) and two coarse-grained soils (Yuma sand and crushed basalt rock) have been used. Classification and gradation data for these soils are shown in fig. 1.

16. Fine-grained soil-water mixtures. These mixtures are prepared by blending (in a pug mill) water with soil that has been previously dried and crushed into fine particles. The mixture is dumped from the pug mill into a soil bin (fig. 2), where it is compacted by a rubber-tired roller. About 95 percent saturation is achieved. In this state, this soil will remain stable for periods of a year or more, if the surface is kept covered with an impervious membrane and the material is infrequently (once or twice a week) sprayed lightly to compensate for moisture losses. This

material can be reprocessed in place for many cycles without any noticeable change in behavioral properties, provided it is not allowed to dry. Spraying of the material is performed more frequently during the reprocessing and testing cycles.

17. Coarse-grained soil-water mixtures. During the past two years, the WES was faced with the problem of producing a soil test section of Yuma sand and one of crushed basalt (fig. 1), both of which had to possess cohesive and frictional strength components. The use of synthetic pore fluids was considered, since it was generally felt that water content levels greater than that present in the air-dry condition, i.e. about 0.5 percent, could not be maintained; however, this fear proved to be unfounded. Mixing was accomplished by spreading the dry sand on a concrete floor, adding water, and blending the water with the soil by using hand tools, including a gasoline-engine garden rotary tiller. The mixture was then placed in a soil bin (fig. 2). By covering the soil when not in use and spraying the surface very lightly and frequently (30-minute intervals) during reprocessing and testing cycles, moisture content up to about 2 percent was easily maintained at a constant level. During idle or storage periods, the material was sprayed once or twice daily.

#### Synthetic soils

18. Fine-grained. Difficulties were experienced at the WES in developing a homogeneous mixture (even distribution of pore fluids) of either the heavy clay or the lean clay with ethylene glycol or glycerin. When the synthetic soils were mixed by running them through a pug mill, as water is mixed with natural soil, they contained lumps of dry material, and increasing the mixing period did not solve this problem. A milling device had to be used, and only small batches of material could be prepared at one time. In some cases reported by others, artificial soils (clay-sand-oil type) produced soil balls when they were reprocessed, and the balls grew in size and number with each reprocessing. To maintain such a mix might involve passing the material through a hammer mill, pug mill, or similar device. In other cases, the fluid separated from the soil solids (commonly called bleeding) when synthetic pore fluids were added in sufficient quantities to produce a purely cohesive material; cost of maintaining

such a mix is high. As mentioned above in paragraph 13, success has been reported in mixing a fine-grained soil (kaolinite) with a mixture of two liquid chemical compounds that are members of a family of solvents or catalysts known as plasticizers. This material did not tend to "ball" or "bleed" and the maintenance requirements were less than those for other synthetic mixes.

19. Coarse-grained. No attempts have been made at the WES to produce coarse-grained synthetic soils. A review of the literature and discussions with researchers who have produced such soils indicate that no particular difficulties have been experienced in preparing and maintaining satisfactory coarse-grained synthetic soils.

#### Comparative Tests of Natural and Synthetic Soils

20. The following paragraphs are limited to a discussion of those tests conducted to evaluate the similarity of engineering properties of natural and synthetic soils. The discussion does not purport to assess the validity of certain types of tests in which synthetic soil was used, e.g. traction performance, forces on tillage tools, etc.

##### Tests by Selig and Rowe

21. Selig and Rowe made a comparative evaluation of selected engineering properties of synthetic and natural soils. Results showed that Atterberg limits for a given soil differ with the pore fluids used for equivalent fluid contents. Further, the compaction curves (density versus fluid content) are different for the different pore fluids. Similarly, the relation of unconfined compressive strength of the compacted (equal compaction efforts) specimens to fluid content varies with the pore fluid used. These investigators concluded that the mixtures of clay and synthetic pore fluids lacked long-term stability.

##### Tests at WES

22. Testing of synthetic soils at the WES included an evaluation of:
- a. The effect of rate of loading on penetration resistance.
  - b. The effect of temperature on penetration resistance.

c. The effect of synthetic pore fluids on shear strength.

d. Long-term stability.

Where possible, results from the tests with synthetic soils were compared with those from tests with natural soils.

23. Effect of loading rate on penetration resistance. The effect of rate of loading on resistance to penetration of the WES cone penetrometer was examined for the two test clays (paragraph 15) mixed with two different pore fluids, glycerin and ethylene glycol, and the penetration resistance of the mixtures of clays and synthetic pore fluids was found to be more rate dependent than that of soil-water mixtures at or near room temperature (fig. 3). The penetration resistance of clay-glycerin mixtures had the highest dependence on the rate of loading. At a rate of penetration of 72 in./min,\* the penetration resistance of both the heavy clay and lean clay samples was about 67 percent higher than at 10 in./min, whereas the lean clay-glycol (stored 6 months) and heavy clay-glycol mixtures showed comparable increases of 25 and 34 percent, respectively. Also, for a given clay-fluid content-penetration speed combination, the penetration resistance was greater for the synthetic soils than for the natural soil-water mixtures.

24. Effect of temperature on penetration resistance. The penetration resistance of the synthetic soils was quite sensitive to changes in temperature, as shown in fig. 4, the clay-glycerin mixtures being the most sensitive for the conditions examined. The general trend was for the penetration resistance to increase as temperature decreased. The greatest change noted was in the lean clay-glycerin mixture; its penetration resistance increased by more than 200 percent when the temperature dropped from 140 to 46 F.

25. Effect of synthetic pore fluid on shear strength. The Cohron sheargraph was used for in situ evaluations of the surface shear strength in both the natural and synthetic soils. In general, the synthetic soils tended to have greater strength than the clay-water mixtures. Shear

---

\* A table of factors for converting British units of measurement to metric units is presented on page vii.

strength evaluation performed with the McRae gyratory machine yielded similar results. For example, when the Cohron sheargraph results at a normal pressure of 10 psi\* were evaluated, the following results were obtained:

<u>Soil</u>	<u>Pore Fluid</u>	<u>Fluid Content %</u>	<u>Shear Strength psi</u>
Lean clay	Water	28	7.5
Lean clay	Glycerin	28	14.0
Heavy clay	Water	37	4.0
Heavy clay	Glycerin	37	10.0
Heavy clay	Ethylene glycol	37	9.0

The gyratory shear tests yielded the following:

<u>Soil</u>	<u>Pore Fluid</u>	<u>Fluid Content %</u>	<u>Shear Strength, psi</u>	
			<u>50-psi Normal Pressure</u>	<u>100-psi Normal Pressure</u>
Heavy clay	Water	37	5	5
Heavy clay	Glycerin	37	17	22
Heavy clay	Ethylene glycol	37	11	18

26. Long-term stability. The brevity of the program and the low funding level did not permit a detailed evaluation of the changes in the engineering properties of the mixtures with time; however, a few observations were made. There was no apparent "bleeding" of the mixtures that were stored for periods up to 12 months. Some balling did occur; but since the soil was not subjected to extensive reprocessing, the magnitude of this problem could not be ascertained.

#### Disadvantages of Synthetic Soils

27. Synthetic soils that are prepared by mixing synthetic pore fluids or binders with one natural soil or an admixture of soils have a number of disadvantages, some of which are:

---

\* The Cohron sheargraph is normally operated in a range of normal pressures from 0 to 15 psi, whereas the gyratory shear device, designed for higher pressures, was operated at normal pressures of 50 psi and above.



- a. Difficulty in the mixing process to achieve a homogeneous mixture, thereby resulting in high initial processing costs.
- b. High cost of synthetic pore fluids and binders.
- c. Bleeding of "wet" mixes that are intended to represent cohesive soil, i.e. pore fluids separate from the mix if it is left standing, and continuous maintenance of the mix is required.
- d. Forming of soil balls in "dry" mixes, such as those used to represent friable soils in agricultural equipment research laboratories, when the mixes are reprocessed, so that after several processing cycles, the material must be removed from the testing line, the balls broken up, and the material completely remixed.
- e. Greater dependency on temperature changes and rate of loading of the penetration resistance of synthetic soils (clay mixed with ethylene glycol or with glycerin) than that of clay-water mixtures.

28. The above comments apply, in the main, to mixes with pore fluids that are more viscous than water and with viscosities more temperature dependent than that of water.

#### Ongoing Research

29. According to a recent report by the State University of New York at Buffalo, a synthetic mix that lacks some of the disadvantages mentioned in the preceding paragraphs is being prepared and used in its facilities (paragraphs 13 and 18). The mix is a combination of kaolinite and Hydrate 121 (a mixture of dibutyl phthalate and dibutyl sebacate). These liquids are mixed in proportions necessary to form a liquid whose specific gravity is one (equivalent to that of water). This synthetic mix presented no serious initial mixing problem, has been stable for almost a year, and shows no signs of deterioration due to reprocessing; however, it has not been evaluated with respect to rate of loading and temperature effects.

30. The researchers have postulated that mixing and stability problems are less severe for Hydrate 121-kaolinite mix than for other synthetic mixes because the molecule diameters of the two constituent liquids of Hydrate 121 approach that of water. Further, the penetration resistance

of this synthetic mix may not be as sensitive to changes in rate of loading and temperature as other synthetic mixes because the pore fluid, Hydrate 121, has a viscosity similar to that of water, and its viscosity is less sensitive to temperature changes than that of other fluids commonly used in synthetic soils.

31. Without a doubt, better synthetic mixes can be had than those commonly used in the past, but each new mix needs to be carefully evaluated. In the opinion of this author, the evaluation requirements are extensive enough in many cases to force a conclusion that the use of natural soils is more economically feasible than the use of synthetic ones.

### Conclusions and Recommendations

#### Conclusions

32. Based on the information that has been compiled from other researchers and the limited amount of data available, the following tentative conclusions were reached:

- a. Synthetic soils do not offer the panacea that earlier researchers claimed or hoped for.
- b. Many mixes lack long-term stability, and thus do not offer economic advantages and cannot be used as standard reference soils.
- c. The penetration resistance of synthetic mixes is very likely to be more dependent on temperature and rate of loading than that of soil-water mixes.
- d. The problems listed in conclusions b and c restrict the usefulness of synthetic soils in development of systems for predicting the behavior of prototype soil-structure (or any soil-foreign object) interaction systems in their natural environment, based on laboratory (model or prototype) testing.
- e. With a little extra effort, natural soils can be maintained in a stable condition for relatively long periods of time.

#### Recommendations

33. Any researcher or consultant, prior to selecting or recommending a synthetic soil, should make certain that he fully understands the

behavioral patterns peculiar to that mix so that the utility of the information produced is not restricted by them.

34. Strong consideration should be given to the trade off between exercising greater-than-normal care in preparing and maintaining natural mixes, i.e. soil-water, and the high initial cost and other problems connected with synthetic soils before any research program involving soils is undertaken.

#### Selected Bibliography

Clark, S. J. and Liljedahl, J. B., "Soil Bins, Artificial Soils and Scale Model Testing," Transactions of the American Society of Agricultural Engineers, Vol 11, No. 1, 1968, pp 198-202.

Hanamoto, B., "Artificial Soils for Laboratory Studies in Land Locomotion," Report No. 20, Nov 1957, Land Locomotion Laboratory, U. S. Army Tank-Automotive Center, Warren, Mich.

Korayem, A. Y. and Reeves, C. A., "Artificial Soils Simulate Natural Soils in Tillage Studies; Parts I and II," Transactions of the American Society of Agricultural Engineers, Vol 9, No. 2, 1966, pp 145-150.

Selig, E. T. and Rowe, R. D., "A Study of Artificial Soils," Preprint No. 95, Oct 1960, American Society for Testing Materials, Philadelphia, Pa.

Turnage, G. W., "Measuring Soil Properties in Vehicle Mobility Research; Effects of Velocity, Size, and Shape of Probes on Penetration Resistance of Fine-Grained Soils," Technical Report No. 3-652, Report 3, Nov 1970, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Wang, C.-T., "Moisture Content Determination for Redsod Artificial Soils," (unpublished contract report), June 1970, State University of New York, Buffalo, N. Y.

#### Personal Correspondence

Ehrlich, I. R., Personal Correspondence, Stevens Institute of Technology, Hoboken, N. J., 1970-71.

Selig, E. T., Personal Correspondence, State University of New York, Buffalo, N. Y., 1970-71.

Wisner, R. D., Personal Correspondence, Deere and Co. Technical Center, Moline, Ill., 1970-71.

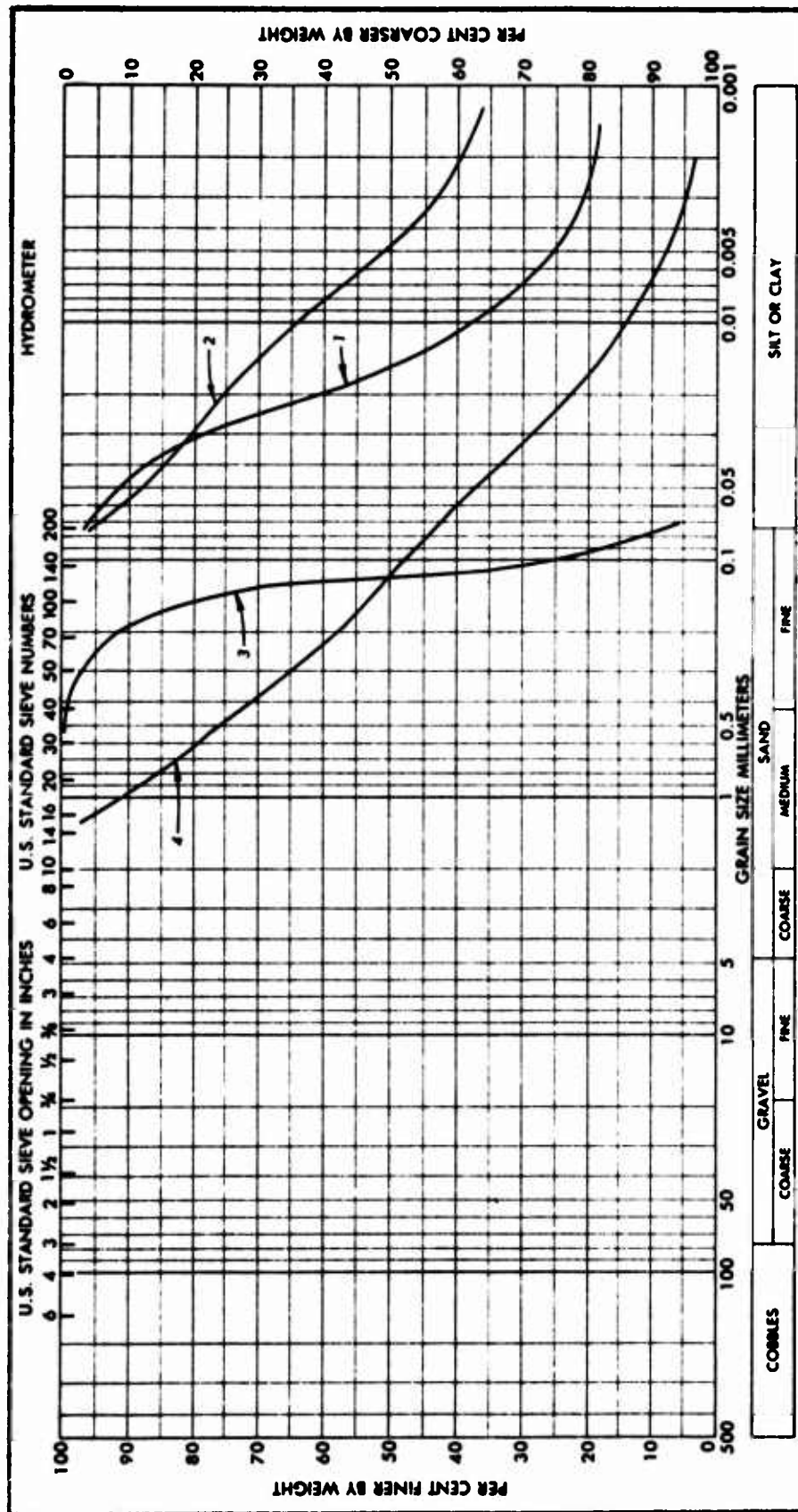
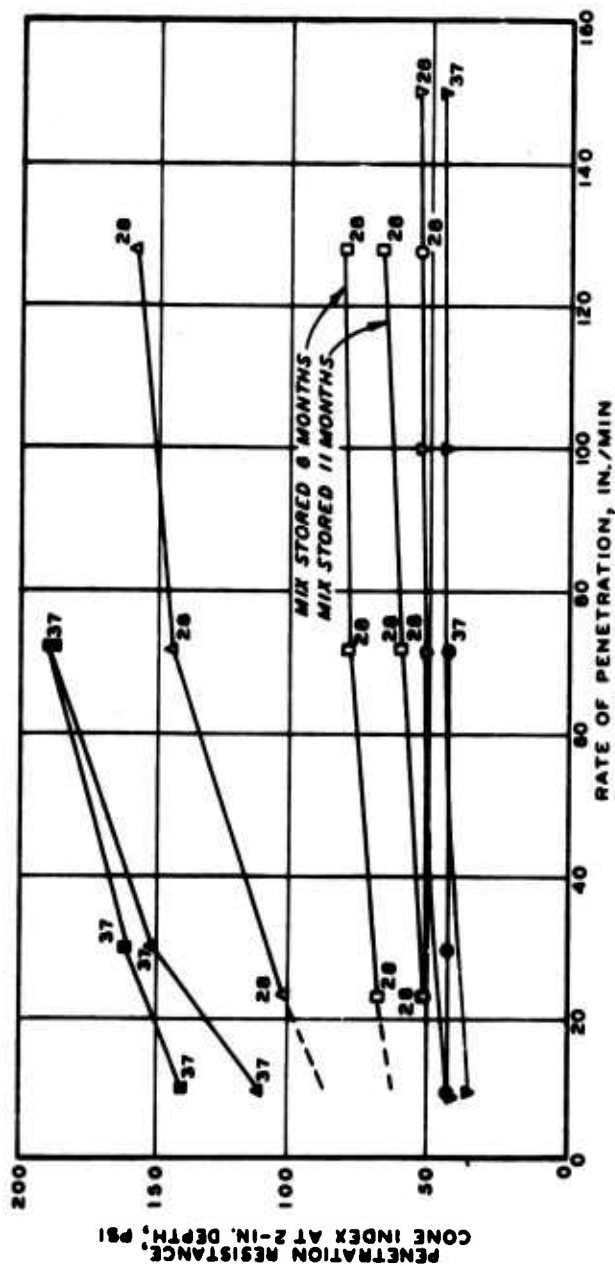


Fig. 1. Gradation and classification data for the test soils



Fig. 2. Soil test bin with right side covered to prevent moisture loss. Note bin in right background completely covered

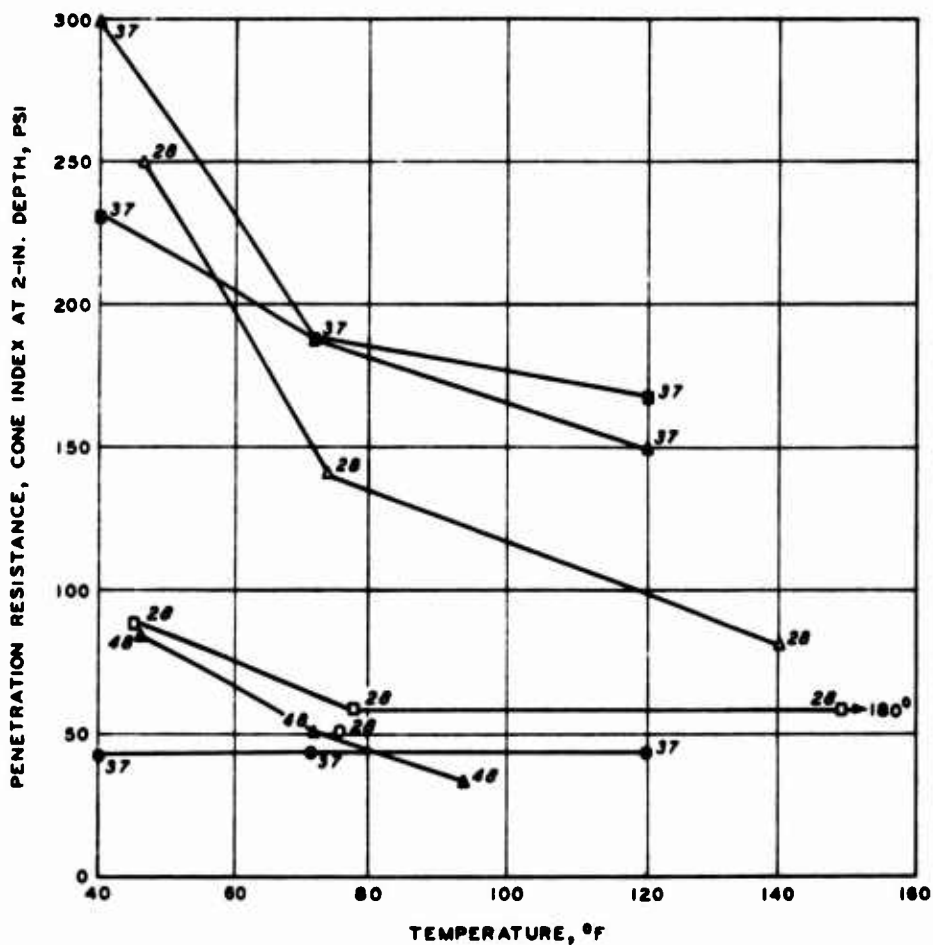


# LEGEND

- HEAVY CLAY AND WATER
- LEAN CLAY AND WATER \*
- ▽ HEAVY CLAY AND WATER \*
- △ HEAVY CLAY AND GLYCERIN
- ▲ LEAN CLAY AND GLYCERIN
- ◻ HEAVY CLAY AND GLYCOL
- ◻ LEAN CLAY AND GLYCOL

NOTE: NUMERALS ON PLOT DENOTE  
FLUID CONTENT IN PERCENT.  
\* COMPUTED RESULTS FROM TURNAGE.

Fig. 3. Penetration resistance versus rate of penetration; temperature = 72-78 F



### LEGEND

- HEAVY CLAY AND WATER
  - LEAN CLAY AND WATER
  - ▲ HEAVY CLAY AND GLYCERIN
  - △ LEAN CLAY AND GLYCERIN
  - HEAVY CLAY AND GLYCOL
  - LEAN CLAY AND GLYCOL
- NOTE: NUMERALS ON PLOT DENOTE FLUID CONTENT IN PERCENT.

Fig. 4. Penetration resistance versus temperature;  
velocity = 72 in./min

-15-